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SCOUR CONTROL AT SKEW BRIDGE ABUTMENTS BY THE USE OF SPUR DIKES

A Report for
C.E. 406 - Special Problems in Civil Engineering
(3 Credit Hours)

by

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Submitted to
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A C K N O W L E D G E M E N T

The present laboratory study was a part of the project on spur dikes being conducted by the Hydraulics Division of Fritz Engineering Laboratory, Lehigh University, and sponsored in part by the firm of consulting engineers, Messrs. Modjeski & Masters of Harrisburg, Pennsylvania.

The author is pleased to extend his thanks to Professor J.B. Herbich, Chairman of the Hydraulics Division and Professor H.R. Vallentine for their kind and valuable guidance and assistance throughout the study, which appreciably eased his work, and for some valuable suggestions for, and corrections in this report. His thanks are also due to the members of the technical staff of the Laboratory for their help.

C O N T E N T S

1. INTRODUCTION

1.1 General

Notwithstanding the fact that each year millions of dollars worth of damage to life and property is caused all over the world by collapse of bridges due to scouring of foundations in times of floods, the undermining of bridge structures still remains a perplexing problem to engineers. First, owing to the inadequacy of the theoretical approach to tackling the problem; second, owing to lack of intensive research to this day to find practical solutions for reduction of this effect; third, owing, probably, to the preoccupation of engineers in thorough design of superstructure only.

But it is a happy augury that it is being increasingly realized that a sound highway bridge design also involves hydraulic considerations for the safety of the bridge foundation, like the possibility of scour, its magnitude, its effect on the stability of the structure, and methods for minimizing this effect. It is well known that constriction of the flow due to embankments and piers in the channel results in a rise in water-level upstream of the constriction, increase in flow velocity in the constricted area, and eddying and separation around the abutments and piers. In times of great floods, this produces severe scouring at the abutments and piers, often with devastating results.

With the emphasis as much as, if not more than, on scour prevention, as on the soundness of superstructure, the designer's objective usually becomes determination of the bridge span, resulting in the least costly and most stable structure, the cost of scour prevention being included. But scour prevention is itself still an enigma because, although some research has been conducted on this aspect, there is lack of reliable data and guidance for predicting the extent of scour under given conditions, and for designing methods of avoiding or reducing its effects.

In recent years the interest of the engineers has been focused on the usefulness of spur dikes in minimizing scour at the abutments by streamlining the flow and establishing uniform velocity distribution through the opening.

1.2 Objective

Owing to various limitations of the present study, our objective was to find the effect of spur dikes of various forms, placed at 60° skew abutments, on the scour around the abutments. The study itself was largely qualitative and rather generalized in nature. It was in continuation of several such studies conducted at Lehigh University over the past three years.

1.3 Limitations

Limitations of the study, imposed by the time available, were with respect to flow geometry, viz:

(i) angle of skew

(ii) depth of flow

(iii) opening between abutments, and

(iv) sand grading

Only the ultimate scour patterns, under the conditions of equilibrium, were recorded.

The qualitative nature of the study can only permit general conclusions, which, although not forming design criteria themselves, will no doubt help in further studies aimed at the same.

2. SURVEY OF LITERATURE AND RESEARCH

2.1 Previous Research

The problem of scour at the bridge foundations really began to draw attention of engineers only in the last decades of the last century. The earliest laboratory study of this problem was a report published in 1894 by Engels in Germany; but a reference was made in that report to some previous research conducted in France by Durand-Claye in 1873. However, these studies were confined to narrow limits and did not go far, either in prediction or in prevention of scour.

The investigation having again lapsed for more than half a century, it was only in 1949 that attempts at serious theoretical, as well as practical, studies began. The U. S. Department of Agriculture published a paper: FLOW THROUGH DIVERGING OPEN CHANNEL TRANSITIONS[1]. About the same time, Posey studied the problem of scour around the bridge piers at the Rocky Mountains Hydraulics Laboratory and published his findings in WHY BRIDGES FAIL IN FLOODS[2]. This was soon followed by the publication of COMPUTATIONS OF PEAK DISCHARGES AT CONSTRICTIONS[3] in 1953, by the U.S. Geological Survey.

The State University of Iowa also began investigation into this problem, and this study was described by Laursen and Toch in their report SCOUR AROUND BRIDGE PIERS AND ABUTMENTS[4]. This was followed by two reports by Laursen in 1958 and 1960, SCOUR AT BRIDGE CROSSINGS[5,8]. More recently Liu, Chang and Skinner conducted laboratory study at Colorado State University and published their report, THE EFFECT OF BRIDGE CONSTRICTION ON SCOUR AND BACKWATER[6] in 1961.

Some of the conclusions derived from these studies regarding mechanism and hydraulics of scouring have been discussed below, under a separate heading.

2.2 Use of Spur Dikes

From research studies on the effect of spur dikes and their actual application in a number of cases, it appears that the dikes streamline the flow through the bridge opening, eliminate separation and eddying, and considerably reduce scour at the abutments and breakwater upstream of the constriction.

The Georgia State Highway Department was the first in 1955, in this country, to sponsor study on the effectiveness of spur dikes; but in their report[9] were given no elaborate details other than that a length equal to 0.08 times the opening at 0° inclination proved the most efficient. Some research seems to have been conducted in Sweden in 1957 by Hartzell and Karamyr, who concluded that dikes some distance away from the abutment end, and at 0° inclination to the direction of flow, give the best results.

Colorado State University commenced studies on spur dikes with a movable-bed model. They reported[11, 12] that an elliptically-shaped dike with an axis ratio of 2-1/2 : 1 was the most efficient for control of scour. It was further concluded that scour depth was inversely proportional to dike length, and that it was a function of the quantity of flow obstructed or diverted by the embankments. A tentative guide for determining the dike length was also given. A limited investigation on 45° skew abutments was also made.

2.3 The Current Program

For the past three years research study on the control of scour at bridge abutments, with spur dikes, has been conducted at the Hydraulics Division of Fritz Engineering Laboratory, Lehigh University, the project being sponsored by the firm of consulting engineers, Modjeski and Masters, Harrisburg, Pennsylvania. The project involved in the beginning, tests on a fixed-bed model only, but later were also made on a movable-bed model.

In the fixed-bed studies with 90° approach, the dike angle of 20° gave the most uniform velocity distribution, and the lowest mean velocity, while the dike length was found to have little effect in the range tested, viz: 18 inches to 36 inches. In the movable-bed studies it was seen that the curved dikes placed along the streamlines nearly eliminated the scour at the abutments. In the case of 60° approach with the fixed-bed model, the velocity distribution was not so uniform when a dike was placed at the upstream side of the downstream abutment only.

Some interesting conclusions were also reached regarding shape, size, and location of dikes for effective control of scour in the case of 90° abutments and fixed-bed model. They are published in detail by the Institute of Research, Lehigh University[13, 14].

3. THEORETICAL APPROACH

3.1 Prevention of Scour

(a) Mechanism of Scour

Scour is basically a consequence of an imbalance between the rate of sediment transport out of an area and the rate of supply of sediment to that area. At a bridge crossing, the area of vital importance is the immediate vicinity of the foundations of the abutments and the piers. The imbalance between the two rates arises from a variety of causes which are so complicated by themselves that they defy a coherent and simplified approach.

There are two kinds of channel constriction scour, (i) general scour, which is caused by a long constriction of flow, establishing a new regime of flow, and (ii) local scour which is caused by a local constriction of flow due to abutment and piers. We shall confine ourselves to the latter only.

Owing to the complexity of the nature of the various factors involved affecting local scour, most of the studies so far are empirical only.

Several investigators have proposed various empirical formulae for the depth of local scour. Some of these express the scour depth as a multiple of Lacey's regime depth D_L in the contracted section.

Lacey proposed the following relationship for computing the maximum scour depth at a contracted section, which he related to the regime flow depth:

$$D_L = 0.47\left(\frac{Q}{f}\right)^{1/3}$$

in which

D_L is Lacey's regime depth for a straight reach

Q is total discharge

f is Lacey's silt factor

With the help of Lacey's formula and his assumption that local scour is proportional to regime flow depth, Khosla proposed the following formula:

$$D_S = 0.9k\left(\frac{Q^2}{f}\right)^{1/3}$$

in which

D_S is maximum scour measured from water surface

Q is discharge per foot width

k is a factor depending on type of obstruction

After establishing the various relationships for scour depths at various points of abutments and piers, Inglis came to the conclusion that the maximum scour is proportional to unit discharge and pier width as follows:

$$D_S = 1.7D\left(\frac{Q^{2/3}}{D}\right)^{0.78}$$

in which

D is the width of pier

Q is the discharge per foot width

Ahmed[7] and Blench[15] similarly relate the depth of maximum scour to a mean flow intensity, and to some extent, on bed material. Laursen[8] on the other hand, concludes that with bed load movement continuing during the scouring process, the maximum local scour is independent of sediment size and flow obstruction. He concluded that the maximum scour depth below the stream bed may be four times the depth of general scour in case of an embankment extending to the edge of the main channel, with neighboring scour holes overlapping; and as much as twelve times when the main channel is constricted, with no overlap of adjacent scour holes.

A recent study by Liu, Chang, and Skinner[6] indicates that the effect of flow velocity on scour may be appreciable, and that if the bed load is appreciable, the constriction ratio has no appreciable effect on scour depth; but if there is no bed load, the limiting scour is a function of constriction ratio.

Thus it is apparent that there is a lack of agreement on the part of the investigators as to how and to what extent the maximum scour depth is affected by each of the three main factors: (i) material size, (ii) flow intensity, and (iii) contraction ratio, which makes prediction of scour all the more difficult.

(b) Dimensional Analysis

Consideration of the phenomenon of local scour with the aid of dimensional analysis, may also prove helpful. The following more important independent variables may be considered to affect the scour:

- h depth of approach flow
- V velocity of approach flow
- B width of channel
- ω representative fall velocity of bed material
- ρ density of water
- μ dynamic viscosity of water-sediment mixture
- g gravitational constant
- d opening ratio
- θ skew angle of abutment
- G geometry of spur dikes

So that D_S, the scour depth, can be related to these variables as follows:

$$D_S = f_1\,(h, \ V, \ B, \ \omega, \ \rho, \mu, \ g, \ d, \ \theta)$$

If h, V, and ρ are selected as repeating variables the above equation may be converted into a group of dimensionless π-terms as follows, with the π-terms arranged in order of their importance:

$$\frac{D_S}{h} = f_2\left(G, \ d, \ \theta, \ \frac{V^2}{gh}, \ \frac{B}{h}, \ \frac{\omega}{V}, \ \frac{Vh\rho}{\mu}\right)$$

But the magnitude of the task of determining the details of this relationship is rather enormous, and the exact relationship can only be established by conducting experiments in the laboratory, which would be time-consuming. Of course, in the experiments, the problem can be further simplified by ignoring terms of minor importance.

3.2 Prevention of Scour

While on the one hand those of the investigators who drew empirical conclusions from their studies on the mechanism and prediction of scour at bridge crossings did not find any accord in their conclusions, and differed on many points regarding the forces affecting scour, on the other hand, many Universities and Institutes - particularly in this Country - sponsored many laboratory studies on the preventive aspect of scour, without going into details of the former. In fact, many States in this Country have actually made successful field application of measures like spur dikes in bridge construction to reduce scour of foundations. In some cases, they are permeable, such as loose rock-fill, timber cribs, rock-fill embankments, and open timber pilings; in other cases, they are impermeable, such as earth embankment and solid timber sheeting.

The application of measures such as spur dikes to control scour at bridge crossings, stems obviously from a preliminary understanding of how the constriction leads to scour at the abutments. Starting from upstream, the water level begins to rise until it reaches a maximum just on the upstream side of the abutments. Therefrom, it gradually decreases throughthe opening, becomes lowest just downstream of the opening, and again becomes normal further beyond. The flow in the upstream separates from the sides and converges towards the opening. Separation again takes place at the entrance to the opening, and the streamlines separating at the sharp entrance form very strong eddies and turbulence at the upstream corners of the abutments. As the outer streamlines leave the walls of the opening, the narrowest width of flow, just downstream of the opening, is less than the opening, thereafter, the flow diverges to its normal width.

It is obvious that the areas around the upstream corners of the abutments are subjected to violent hydrodynamic action of eddies and turbulence, producing scour of the bed.

Thus, some of the most pronounced effects of constriction are: (i) rise in the water level upstream, which, while gradually decreasing through the opening, produces greater velocity and greater sediment-carrying capacity, and (ii) distortion of flow through the constriction, resulting in non-uniform velocity distribution, due to eddies and separation at the sides.

Obviously then, the problem consists in establishing the continuity of flow through the constriction to guide the flow smoothly, to create uniform velocity distribution, eliminating eddies and separation. To this end, the various laboratory studies have concurrently established the usefulness of spur dikes of certain shape and size, and placed at a certain location; though there are diverging opinions about the size, shape, and location of spur dikes which are dependent on so many factors, such as geometry of embankments, size of bridge opening, flow intensity in the flood plain, etc.

4. MOVABLE-BED STUDIES

4.1 Description of Equipment

A short account of the various units of the testing equipment used for the study is given below.

(a) Head Tank, Motor and Pump

An overhead tank supplied water to the testing tank by gravity. A constant head was maintained in this tank by an overflow channel leading directly to the sump.

The pump used was a De Laval, model 10/8, with a maximum 1750 rpm and a capacity of 1800 gpm against a head of 70 feet; this pump was driven by a 25 H.P. Westinghouse model HF motor with a maximum of 1720 rpm.

(b) Venturi Meter

Located adjacent to the testing tank was an 8-inch by 5-inch Venturi meter which was connected with the head tank by an 8-inch iron pipe. It was calibrated to read

$Q = 1.465 \sqrt{\Delta H}$, where

Q is discharge of water in cfs

ΔH is differential height in manometer in feet of liquid

(c) Testing Tank

The testing tank available for use was 35 feet long, 10 feet wide, and 2 feet deep, and served as a flood plane across which a constriction could be placed. A recessed section was formed in the central 10-foot length by raising the floor of the tank by 5 inches on either side of this section. When a sand lay depth was spread on the floor, this gave the test section a 7-inch deep sand layer, which was sufficient to measure the anticipated scour.

A baffle made of wire gauge and filled with well-graded stones, was placed at the head of the tank so as obtain a uniform flow across the width of the tank. That this served the purpose was testified by measurements of velocity in the preliminary testing in the previous studies. A tailgate at the downstream end of the tank regulated the water level in the tank.

(d) Abutments and Dikes

Vertical 45° wing-wall type abutments, so commonly used by the Pennsylvania State Highways Department, were selected for this study. The abutments and the dikes, which were one foot high, were made of 20-gauge galvanized iron. A circular block was placed at the upstream end of the dike for all tests, with a view to minimizing separation at that end. The dikes were attached flush with the edges BC and FG of the abutments. (Fig. 1).

The abutments were skewed at 60° with respect to the direction of the flow.

4.2 Method of Testing

Before the commencement of the tests, several points had to be considered and settled regarding the procedure for the tests; some of them were conditioned by the limitation of the study, others were established by previous studies here and elsewhere.

(a) Bed Material

The bed material used in the tank was a New Jersey medium sand with an average diameter of 0.30 mm. The grain size distribution curve of the sand is shown in Fig. 2.

(b) Running Time for Tests

It has been shown that the depth of scour caused by a contracted flow increases rapidly with time, though the rate of scour decreases rapidly as the depth increases. In Figures 3 and 4 are shown two curves of scour depth plotted against time, one with the bed-load supply in the scour hole, and the other without it. After a certain period of time, the increase in scour is so small that the scour depth may appear to have reached a limit.

It was reasonable to choose from the graphs a practical value of the running time for tests, within which most of the scour took place. A value of six hours was chosen, since the increase in scour depth after this period was found to be insignificant.

(c) Critical Scouring Velocity

A laboratory experiment was performed in connection with a previous study to determine the critical scouring velocity in the 10-foot wide flume, described above. The bed material has already been discussed.

The particles started moving erratically at a velocity of 0.82 fps, and scour was established at 1.02 fps. This velocity agrees closely with the critical scouring velocity found in the USSR data for particles of 0.30 mm. average size. (in 1936 a report STANDARDS FOR PERMISSIBLE NON-ERODING VELOCITIES was published in Moscow, USSR, by the Bureau of the Methodology of the Hydro-Energy Plan. The values shown therein are for well-seasoned channels of small slopes and depths less than 3 feet). A comparison of the two data is as follows:

	Lehigh University Data	USSR Data
Critical Velocity	1.02 fps	1.10 fps

Thus the velocity of 1.10 fps was picked up as the critical scouring velocity. The depth of water in the tank for all tests was 3 inches.

(d) Opening Between Abutments

As previously stated, it was possible to work with only one opening, which was chosen as 41-1/2 inches. This was the middle of the three openings; 23-1/2 inches, 41-1/2 inches, and 57-1/2 inches, on which previous work was done.

4.3 Description of Tests

In all seven tests conducted, the first one being without the dikes in order that the general scour pattern could be determined, and later on the effectiveness of the dikes could be judged.

First, the abutments were firmly secured in position at 60° to the normal flow direction, with the opening between the abutments adjusted to 41-1/2 inches.

The sand bed in the tank was carefully leveled, first by hand tool and then by a wooden board hung from a bridge moving over the tank. A point gauge which was calibrated to read up to 0.001-foot, and which was attached to the bridge, was used for levelling the bed, as also for contouring the scour pattern.

In order to establish the flow slowly and gradually, the tailgate end was first raised, and then water in the tank was diverted, little by little, through the baffle. After the full flow of 0.952 cfs was established, the tailgate end was lowered and water level adjusted to 3 inches in the test.

Water was gradually stopped after six hours of run, and then the scour pattern was contoured at an interval of 0.1-foot, although sometimes a closer interval was also adopted. After each test, several photographs of the scoured bed were taken, and photo-mosaics prepared. The scour pattern and the effect of dikes in connection with various tests can be judged from Figure 5 through 11.

This procedure was common for all the tests.

In all the tests it was observed that, as was proved by previous laboratory studies, the scour at first increased rapidly with time, though with a rapidly decreasing rate. In fact, most of the scour took place within the first 4 or 4-1/2 hours, after which the movement of the bed-material was so small that it seemed to pass into what Liu, Chang, and Skinner (in Reference 6) describe as the second stage of scour-formation, i.e., establishment of scour.

A general view in plan of the flume with the abutments is shown in Figure 1.

<u>Test 1</u> (Fig. 5)

Some time after the test was started, it became evident that the conditions of scour would be much more severe for the case of skewed abutments than for right-angled ones. With the corners of the abutments lettered as shown in Figure 1, it was noted that eddying and turbulence along the edge FG of the downstream abutment was strongly pronounced, and resulted in separation of flow at this point. But what was, however, more surprizing, only slightly less severe was the effect of eddying and turbulence at the upstream corner B of the upstream abutment.

Consequently, both of these areas were heavily scoured, up to the order of, and beyond, 0.4 and 0.3 feet, respectively. Scour in the center of the opening, down to the downstream sections, was only mild, up to and beyond 0.1-foot. Deposition took place downstream of both abutments, roughly starting from corners D and H, and running approximately parallel to the flow.

A glance at the figure will suffice for the non-uniform nature of the velocity distribution across the opening to be clearly imagined and visualized. The result was localized high velocities along the edges, accompanied by eddying, turbulence, and separation.

The problem, thus, resolved into how the dikes could be fitted at the abutments to reduce this non-uniformity, to eliminate separation, and to minimize scour to the maximum possible extent.

Test 2 (Fig. 6)

To proceed in a systematic manner, we first concentrated our attention to the downstream abutment, only to find the extent of the usefulness of the dike there, and left out the dike at the upstream abutment.

For this test, a dike of 18 inches in length was chosen and attached to the abutment at a 0° inclination, i.e., parallel to edge FG. A round concrete block 6 inches in diameter was placed at the upstream end of the dike to eliminate separation there.

As was to be expected, there was practically no difference in the scour at the unprotected upstream abutment. But the effect of the dike was immediately felt on the downstream one, the scour being considerably reduced at that side. However, there were still mild turbulence and separation at the downstream corner on, and, although milder in comparison with the unprotected abutment, it was obvious that it was sufficient to result in a good amount of scour in a prototype. It was thought that a small stub dike at this downstream corner might probably improve the condition considerably.

Considerable scour at the end of the dike around the concrete block, of course, did nothing to indicate that the block was not effective; it might be only that the length of 18 inches, chosen for the dike, was insufficient to reach sections of lower velocity upstream beyond. And, although a good design should eliminate scour at the end of the dike also, failing which the dike and eventually the abutment itself, which it is supposed to protect, will collapse; we were not concerned with the length of the dike, which is governed by both safety and economy. That would be quite another part of the project, requiring careful attention and considerable time.

Except for this, the general scour pattern, as well as deposition, were much the same in previous tests.

<u>Test 3</u> (Fig. 7)

For this test, the dike angle was changed to 15° inclination to gauge the variation in the effect of the dike. Otherwise the arrangement was the same as in the previous test.

But the change in dike angle in no way brought appreciable change in the general nature of the scour pattern observed in the previous test, which was rather not what was expected, not to say anything about its improving the situation. In fact, on the contrary, it was observed that scour around the downstream corner G went slightly - though only slightly - deeper, perhaps due to more turbulence there.

It must be mentioned, in passing, that it was observed that scour at the upstream abutment was slightly reduced. But whether it was accidental, or due to change in dike angle at the downstream abutment remains uncertain. Generally the change in the set-up at the upstream abutment is more apt to have an effect on the downstream one than vice versa - and this was proved in the course of the latter tests.

No other changes were observed.

Test 4 (Fig. 8)

For this test dikes at both the abutments were attached - the one at the upstream abutment was elliptically-shaped with axis-ratio as 2-1/2 : 1, as it was thought that the curved dike was likely to be more effective owing to the skewness of the opening; while the one at the downstream abutment was as before, at 0° inclination and 18 inches long. The elliptical dike had an 18-inch long major axis.

The elliptical dike at the upstream abutment proved to be the most effective, not only did it completely eliminate scour at the abutment, but there was in fact a good amount of deposition, starting beyond the abutment on the upstream side, and going downwards as usual, parallel to the flow. But heavy scour still concentrated at the end of the dike.

As for the downstream abutment, the scour actually increased - it was more than in the previous two tests. This was probably the influence of the dike at the upstream abutment, which made the problem more complicated; because, although the elliptical shape chosen for the upstream dike was most suitable for the upstream abutment, its shape would have to be determined in context of its influence downstream also.

<u>Test 5</u> (Fig. 9)

The only change for this test was in the dike angle at the downstream abutment, the new angle being 15°.

This change brought in more severe eddies and turbulence at the downstream corner H of the downstream abutment, with the result that scour was much more pronounced at this corner despite the dike. It was evident that any further change in the dike angle would only aggravate the situation. It was also observed, from the last two tests, that the upstream dike must have influenced and distorted the flow pattern further in such a way that the flow was diverted towards the downstream abutment with localized high velocities. The result was that while there was deposition starting well in the center of the opening and increasing towards the upstream abutment and downwards, the other half of the opening towards the downstream abutment was scoured appreciably, in spite of the downstream dike.

Test 6 (Fig. 10)

Many changes were made for this test. The dike length was reduced to 12 inches for both. The downstream dike was at 0° inclination, while the upstream one was elliptical with axis ratio 2 : 1, the major axis being 12 inches. The circular blocks at the end of the dikes were of smaller diameter, 3 inches.

The smaller dike length did not essentially affect the general scour pattern, except that the upstream dike was so shaped and of such small length, that the scour at the end of the dike reached the abutment from behind. It would appear that at least for the upstream abutment a longer dike is not necessary as such, to eliminate the scour in front of the abutment, but only to save the abutment from the scour from behind the dike.

The scour at the end of the dikes was not affected by the smaller diameter of the circular blocks placed there, which makes bigger blocks quite unnecessary.

Test 7 (Fig. 11)

The original shape and size for both dikes were again adopted for this test - elliptical shape with axis ratio 2-1/2 : 1, and major axis 18 inches long, for the upstream dike, and straight shape with 18-inch length for the downstream one. The latter was placed at a 5° inclination on the opposite side, i.e., towards the center of the opening. A small stub dike, 4 inches long, was placed at the downstream corner.

The setup for this test, with particular shape, size, and location - adopted for the two dikes - proved to be the most effective. Scour was almost eliminated at the abutments. The scour was transferred into the middle of the channel because both dikes deflected the flow away from themselves towards the center of the opening. There were still mild eddying and turbulence at the end of the stub dike, where separation of flow occurred, consequently this portion was considerably scoured.

This test gave the best and most desirable result to eliminate almost complete the scour at the abutments.

5. ANALYSIS OF DATA

5.1 Results and Comments

From the very beginning of this study, it became quite clear that the flow pattern was very much different from the 90° approach, and that the resulting increase in eddying, turbulence, and separation of flow would cause more severe scour in this case.

A comparison of the results of the two approaches revealed at once that the general scour pattern was quite different in both cases, and in the present case the scour in the vicinity of the abutments was far too deep for the structure to remain safe and stable, even at somewhat lower discharges. In particular, the bed was scoured equally all around the downstream abutment, though as expected, the corners G and H were worst affected. For the upstream abutment, while the downstream corner C was but little affected, the scour was by no means much less at the upstream corner B. The central portion of the constriction was but mildly scoured in comparison with the vicinity of the abutments. Thus it would seen only reasonable to assume that the flow through the constriction would be much more distorted and velocities more localized and concentrated at the sides.

Due to the change in the angle of the abutments, and consequently in the scour pattern, the nature and the extent of usefulness of the dikes were also altered. Two marked points of difference were observed. First, unlike the 90° approach, the flow was constricted through a much longer section of the flume along its length, i.e., from corner B to G. Second, it no longer took a longitudinal path through the constriction, but was deflected by the upstream abutment towards the downstream one, so that the net result was that the flow was centralized through a very narrow channel of the constriction just near, and adjoining, the downstream abutment. As usual, the vicinity of the sharp corners of the abutments was the most troublesome area, from which the Carle-Kable report[13] concluded that the 45° wing wall type abutments were inferior and actually conducive to more scour.

This flow concentration on one side only was very well demonstrated by the resulting scour - the bed being scoured in a narrow strip which curved from the upstream abutment towards the downstream one, and passed adjacent to the latter to the downstream side.

From this it was clear that not only the shape of the dikes would have to be quite different from a 90° approach, but the shape of the two dikes at the upstream, as well as the downstream abutments in the present case, also would have to be different to channel the flow into the center of the constriction. For one thing, a straight dike of 0° inclination at the upstream abutment would only have aggravated the situation by not only more diverting, but literally throwing most of the flow onto the other side.

So long as the upstream dike was left out in the first few tests, insertion of a straight dike at 0° inclination at the downstream abutment considerably reduced the scour in its vicinity, though the dike did not prove as successful as in the 90° approach and the bed was still scoured to a large degree, the equivalent of which, in a prototype, would be sufficient to endanger the bridge structure, probably because the flow was still observed to be confined more or less on one side. The change in the downstream dike angle to 15° inclination only helped the scouring tendency of the flow slightly more, for which reason further change in the dike angle was considered undesirable, and was dropped.

While in the 90° approach no dike at an abutment would affect scour at the other, the reverse was observed in the present case, though the straight dike at the downstream abutment had already considerably improved the situation there. An elliptically-shaped dike with axis ratio 2-1/2 : 1 at the upstream abutment, completely eliminated the scour near its vicinity (there was even a good amount of deposition at the abutment itself); but while it made the upstream abutment completely safe from scour by being a further obstruction to flow at this point, and by diverting it further towards the opposite side, it increased scour to some extent at the downstream abutment. But this was the best shape for this dike to eliminate scour at the upstream abutment and to improve the general situation, because further deflection of the dike either to the left or to the right by changing the major axis would only be conducive to more deteriorating effects. On the other hand, if a circular shape was adopted, the scour at the end of the dike (which would occur in a reasonably short dike) would undermine the abutment, which it would reach from behind, while on the other hand a more elliptical shape would further divert the flow to the opposite side.

So it was thought best to leave this shape as it was, and to concentrate attention on the shape of the downstream dike.

Though it was observed that more deflection of the straight downstream dike from its 0° position was instrumental to more scour, it was thought desirable to determine the effect of a curved dike also at the downstream abutment; but insertion of a curved dike with axis ratio of 3-1/2 : 1 had such a bad effect that the presence of the dike itself was virtually offset by the bed in the vicinity of the abutment, particularly the downstream corner G, being scoured to a great extent.

From the tests so far, and the results therefrom, it was logical and reasonable to assume that a straight dike at the downstream abutment with an inclination of certain angle on the opposite side, i.e., towards the constriction instead of towards the side of the flume, might divert a portion of the flow, passing adjacent to the downstream abutment, towards the opposite side, i.e., the center of the constriction and help in offsetting the effect of the flow deflected by the upstream abutment, thus channeling the bulk of the flow through the center of the constriction.

Accordingly, a test with a straight downstream dike with a 5° inclination towards the center of the constriction, and with a short stub dike of 4 inches length at the downstream corners was run, which proved to be highly successful in reducing the scour to a reasonably safe limit (Fig.11). That in comparison with the sides, the central portion of the constriction was much more scoured, leaving the abutments practically untouched, proved the effectiveness of this particular location and shape of both dikes.

In all cases, considerable scour was observed at the ends of the dikes, in the presence of which no bridge could be considered safe and stable, because scour of the dikes would ultimately cause collapse of the bridge itself.

But this aspect was more tied up with the determination of the dike length, for which reason it was left for future research.

There were eddying and separation at the end of the stub dike, where a good amount of scour occurred. It was felt that a curved stub dike which would more or less resemble the downstream portion of a spill-through abutment, would be more effective with the absence of sharp and abrupt changes in the boundary.

It was observed that the circular blocks of smaller diameters, which were attached at the end of the dikes, did not in any way adversely affect the scour, and might be considered more useful and economical instead of the bigger blocks.

5.2 Conclusions and Summary

Based on this study, the following tentative conclusions may be made:

(i) The condition in a bridge with skewed abutments would be much more severe than in a bridge with right angled abutments, and the scour would occur at comparatively low discharges.

(ii) Dikes at both the abutments are necessary. The most effective shape for the upstream dike is elliptical with axis ratio 2-1/2 : 1, and that for the downstream dike is the straight at 5° inclination towards the center of the opening. A stub dike, probably curved in shape, is necessary at the downstream corner G of the downstream abutment.

(iii) Dikes with such location and shape help in channeling the flow through the center of the opening in a longitudinal direction.

(iv) For the upstream abutment, although a shorter dike is quite sufficient to eliminate scour in front of the abutment, scour at the end of the shorter dike reaches the abutment from behind; for this reason only a longer elliptical dike would be required there.

5.3 Future Research

Due to the limitations of the study, many points had to be left out from consideration. Future studies may well be conducted on these aspects:

(i) The effect of the variation in the opening on the scour pattern is to be determined.

(ii) Without a proper criterion for deter tion of the dike length, the problem would be only half-solved.

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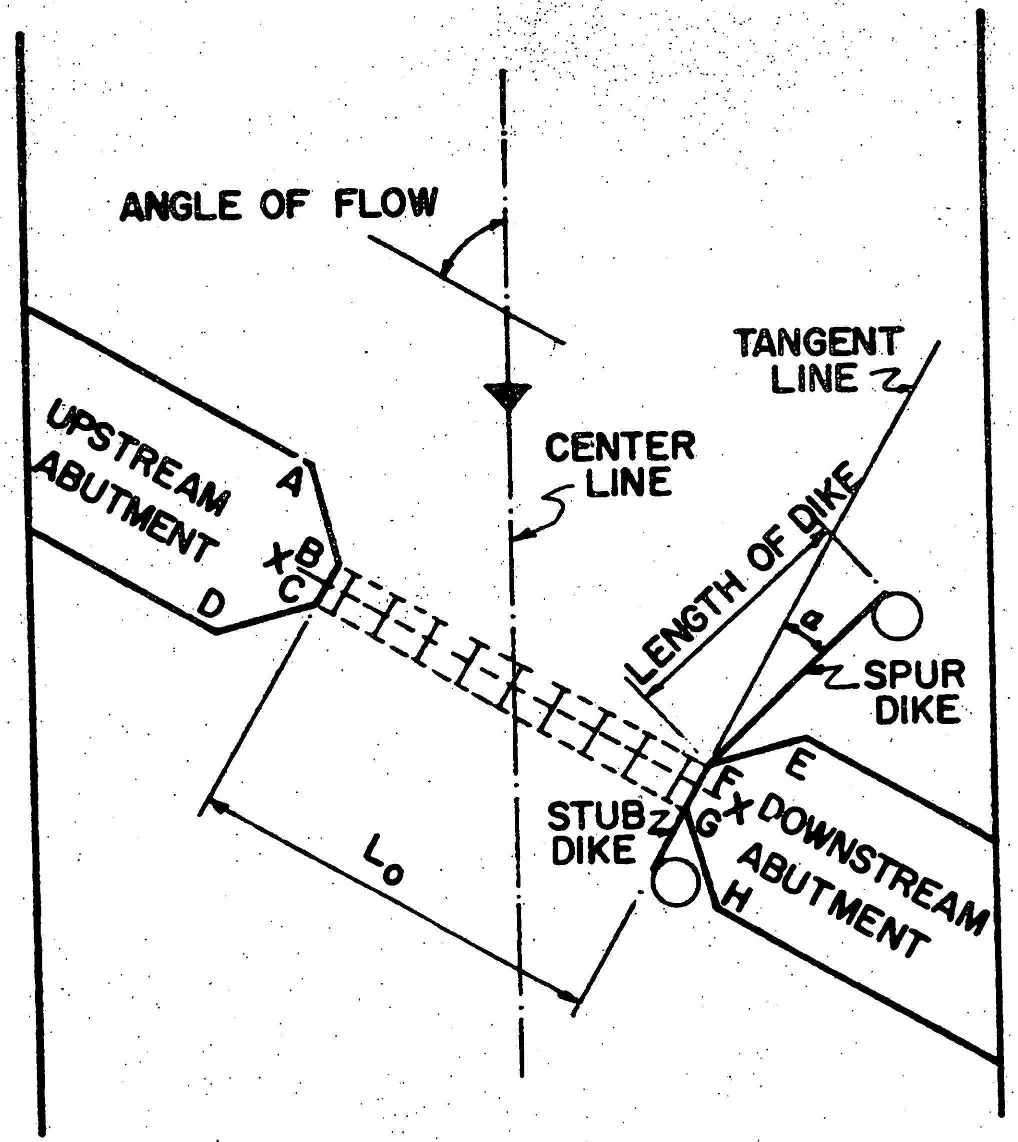
A P P E N D I X



DEFINITION SKETCH FOR SKEWED ABUTMENT

FIG. 1

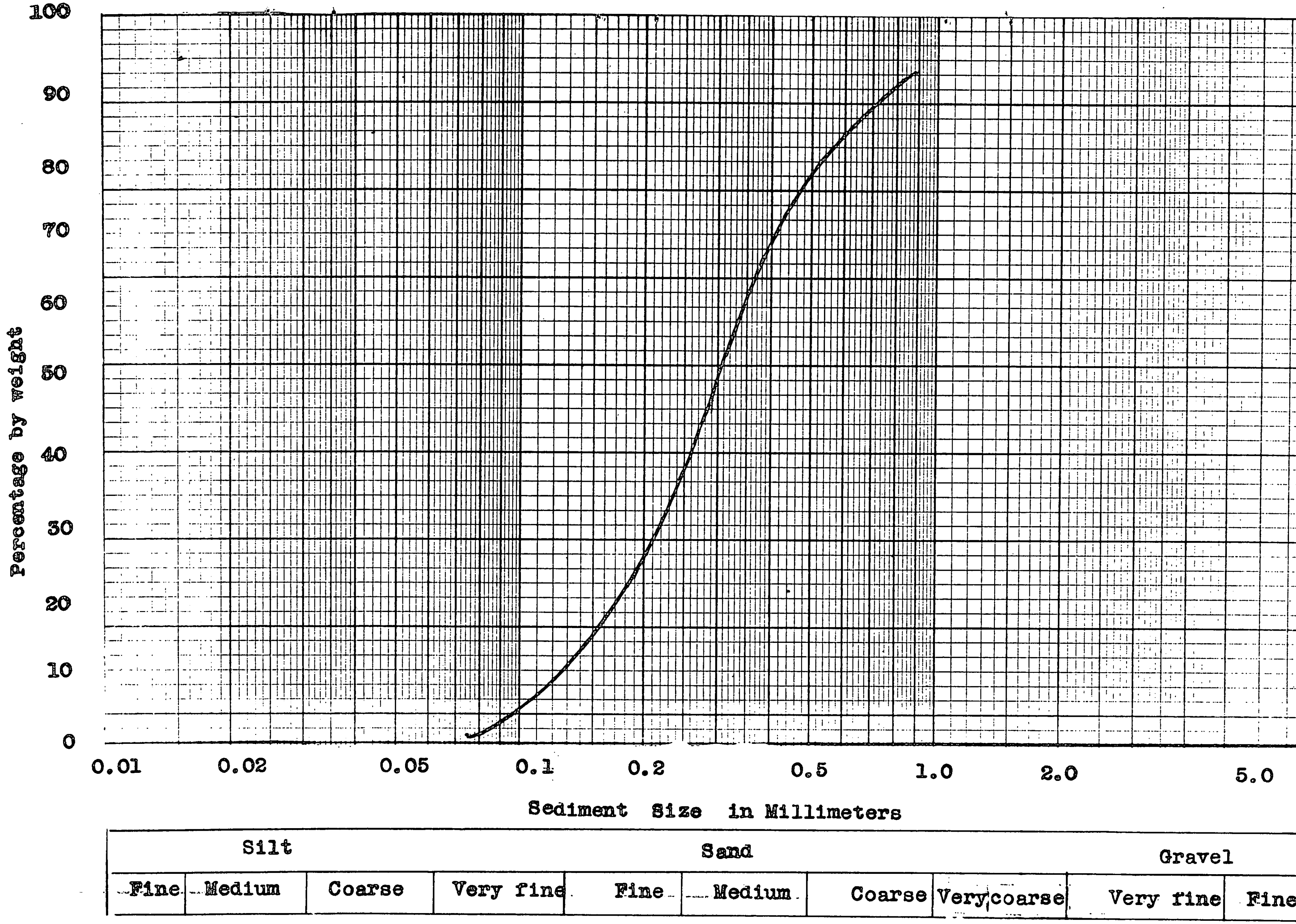


FIG. 2 GRAIN SIZE DISTRIBUTION CURVE

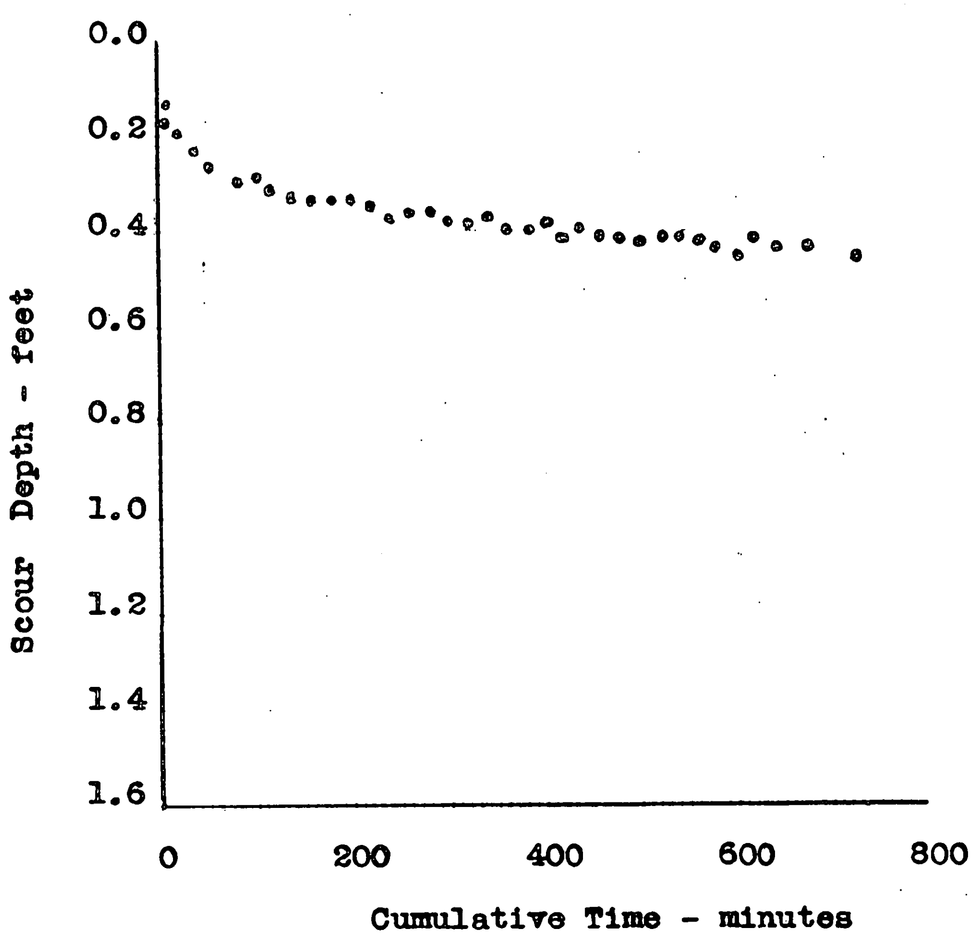


FIG. 3 NO SEDIMENT SUPPLY

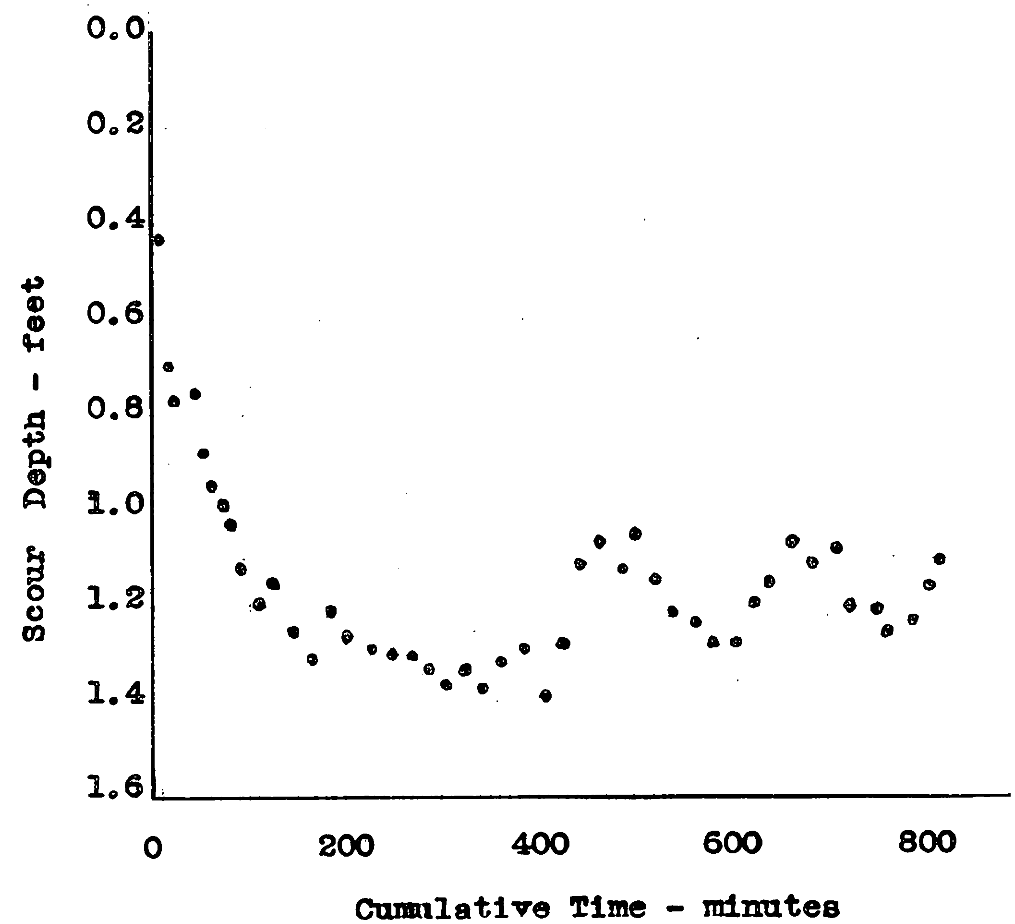
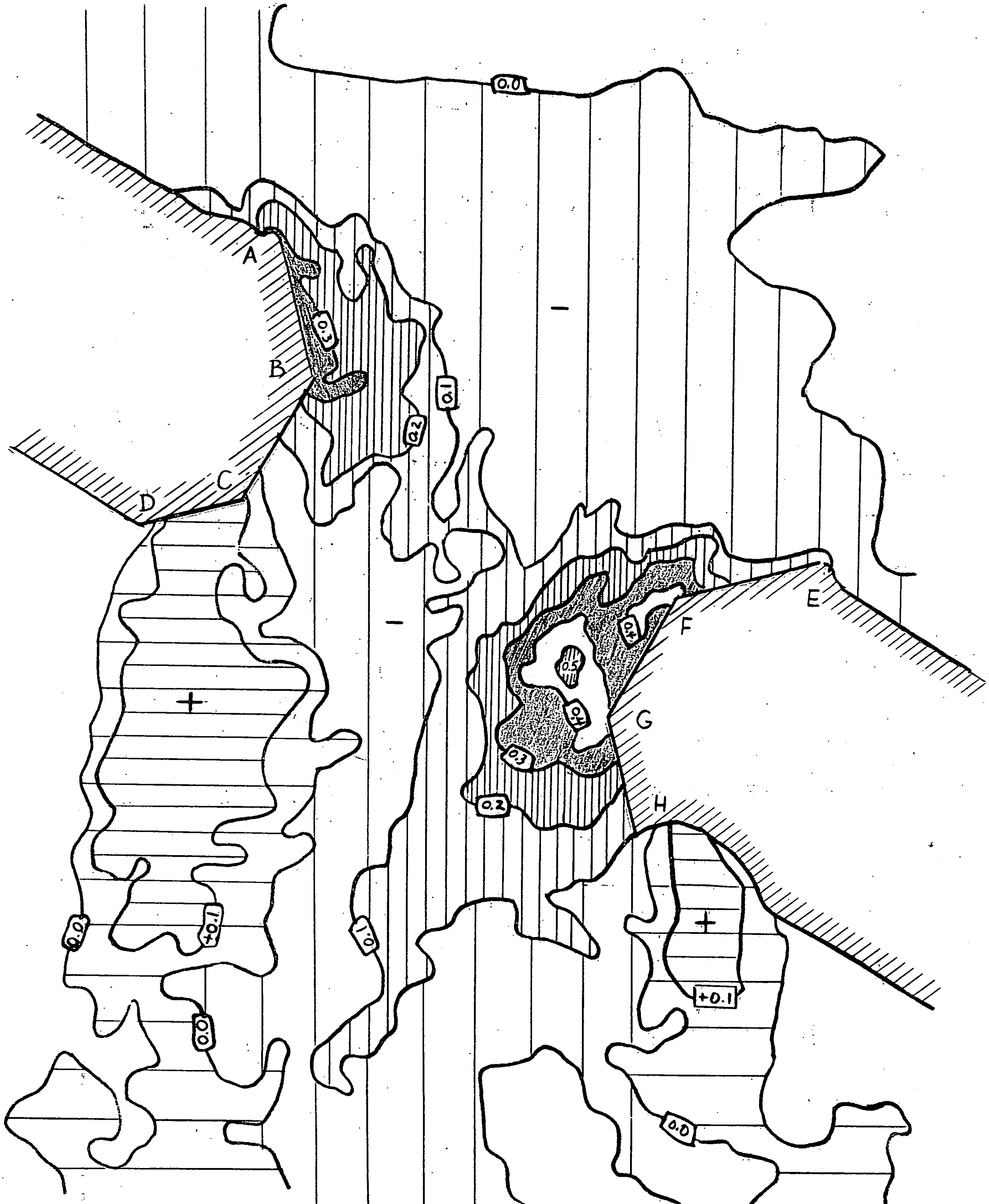
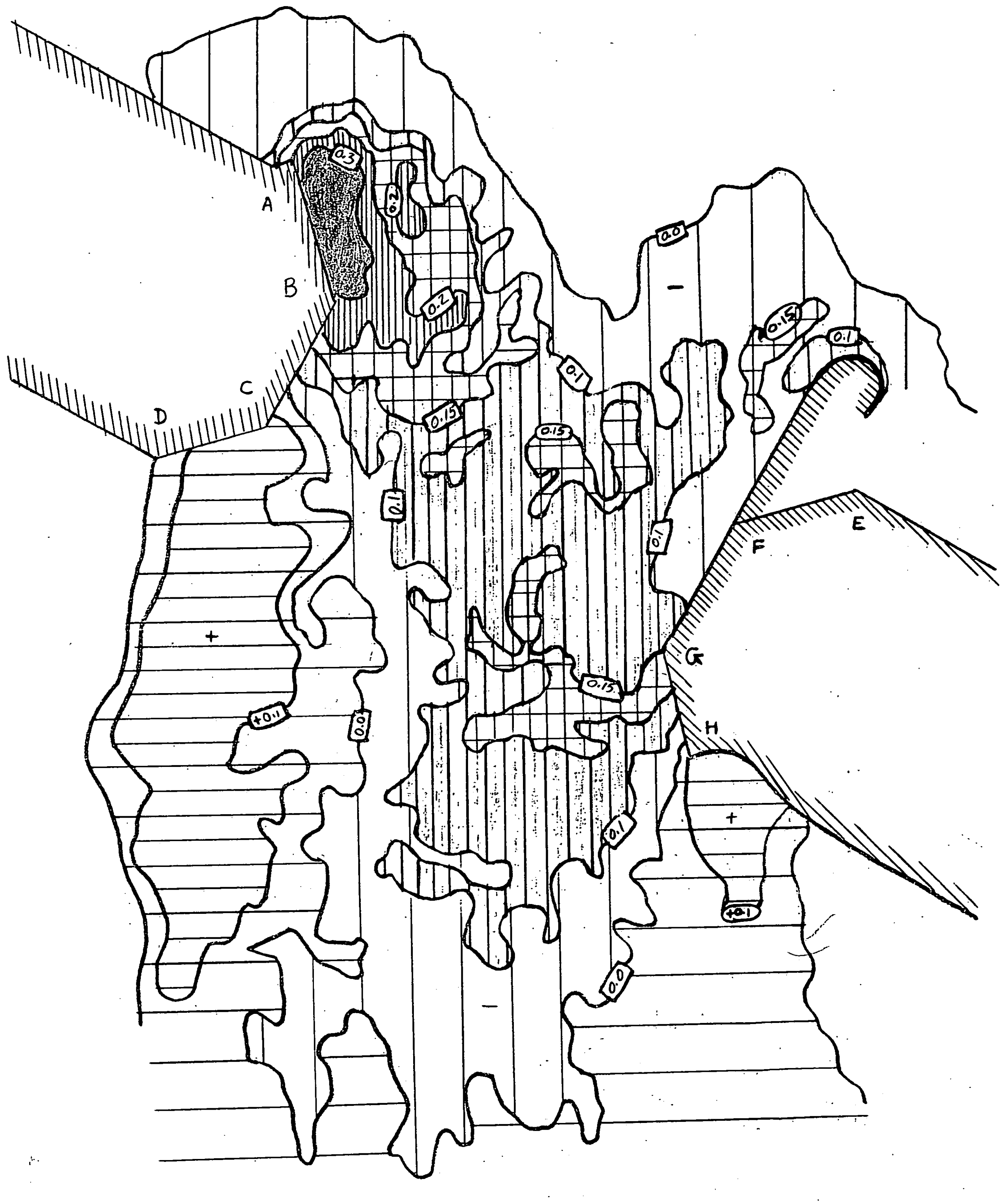


FIG. 4 WITH SEDIMENT SUPPLY

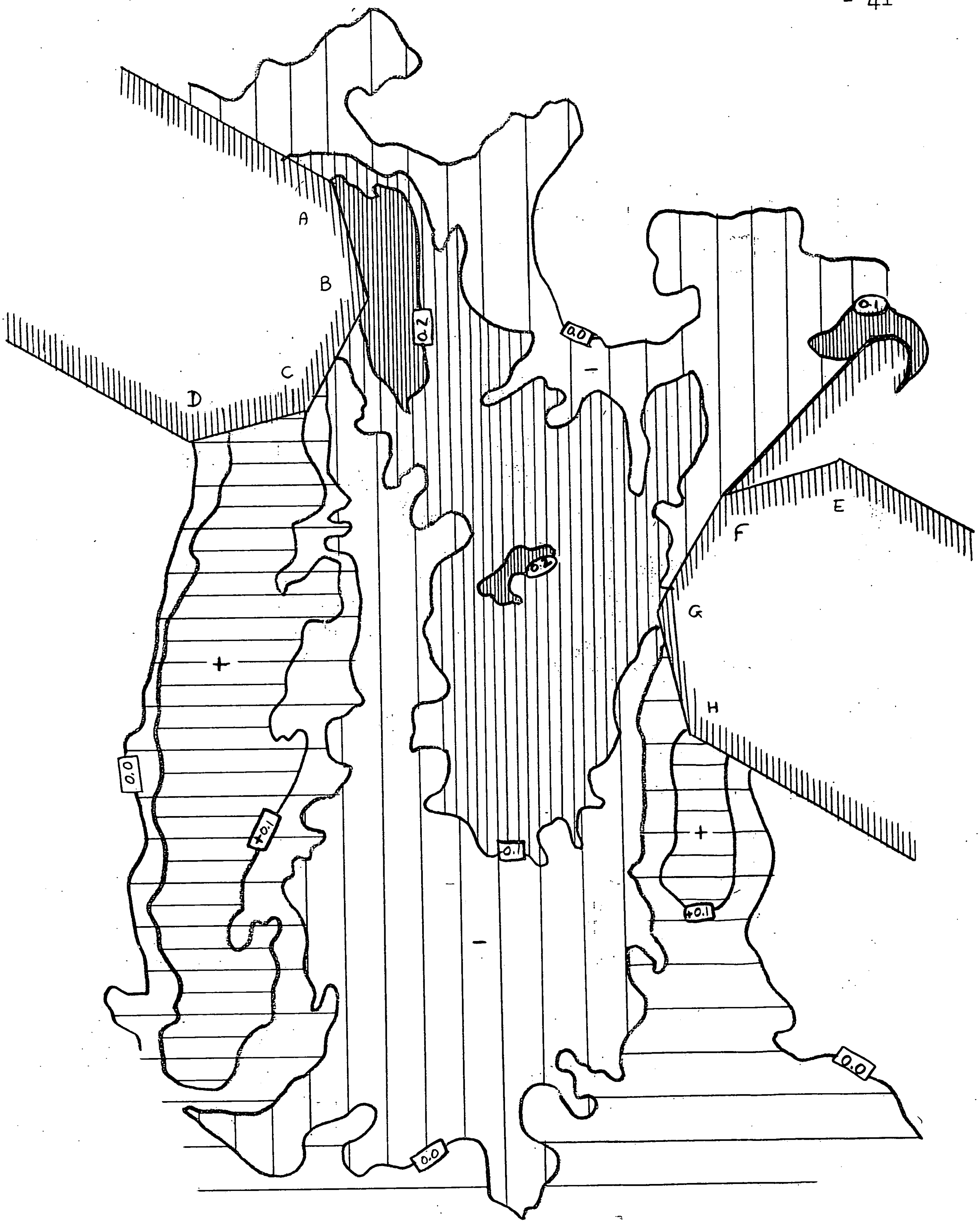
Figures taken from Reference



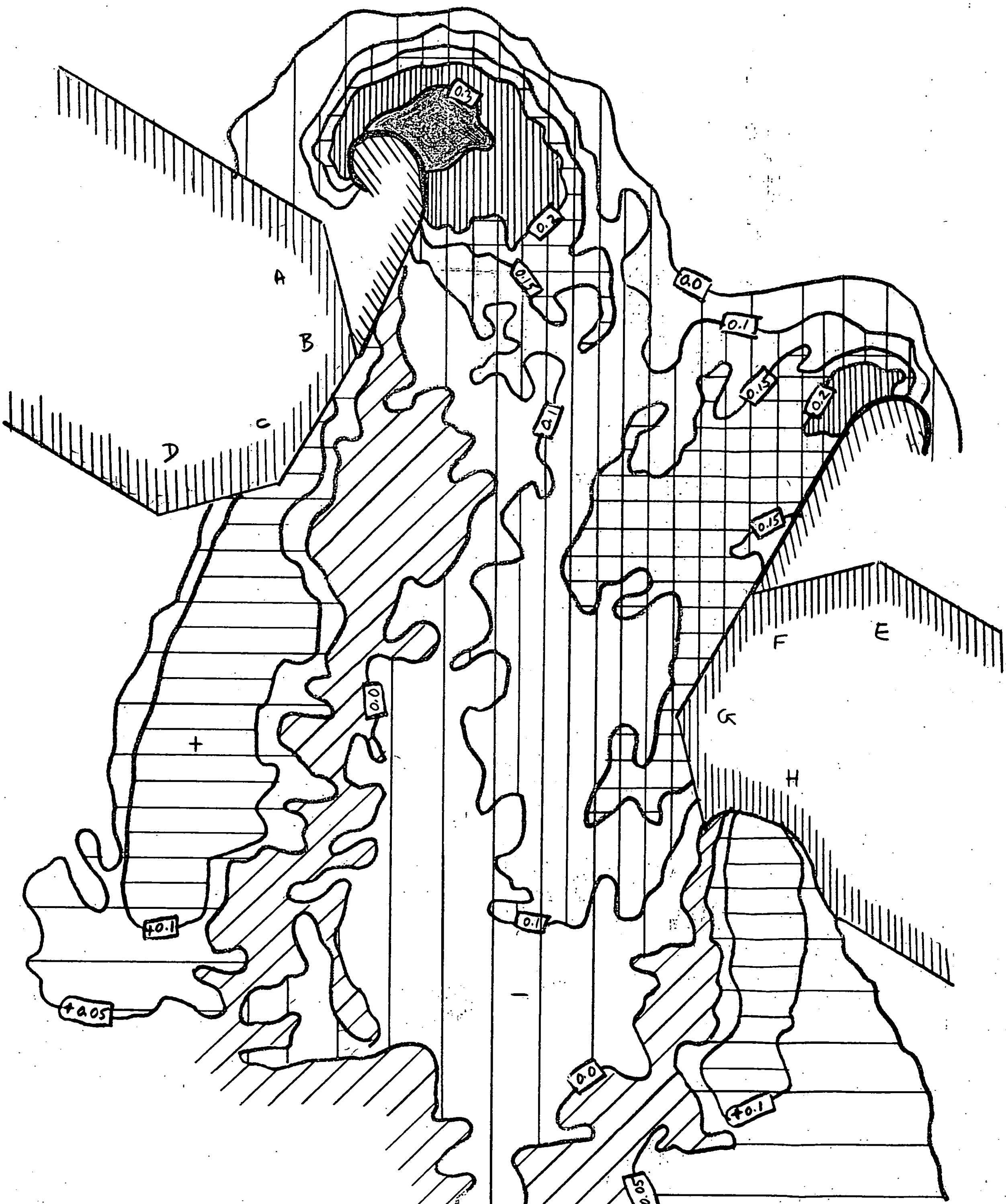
TEST 1: FIG. 5



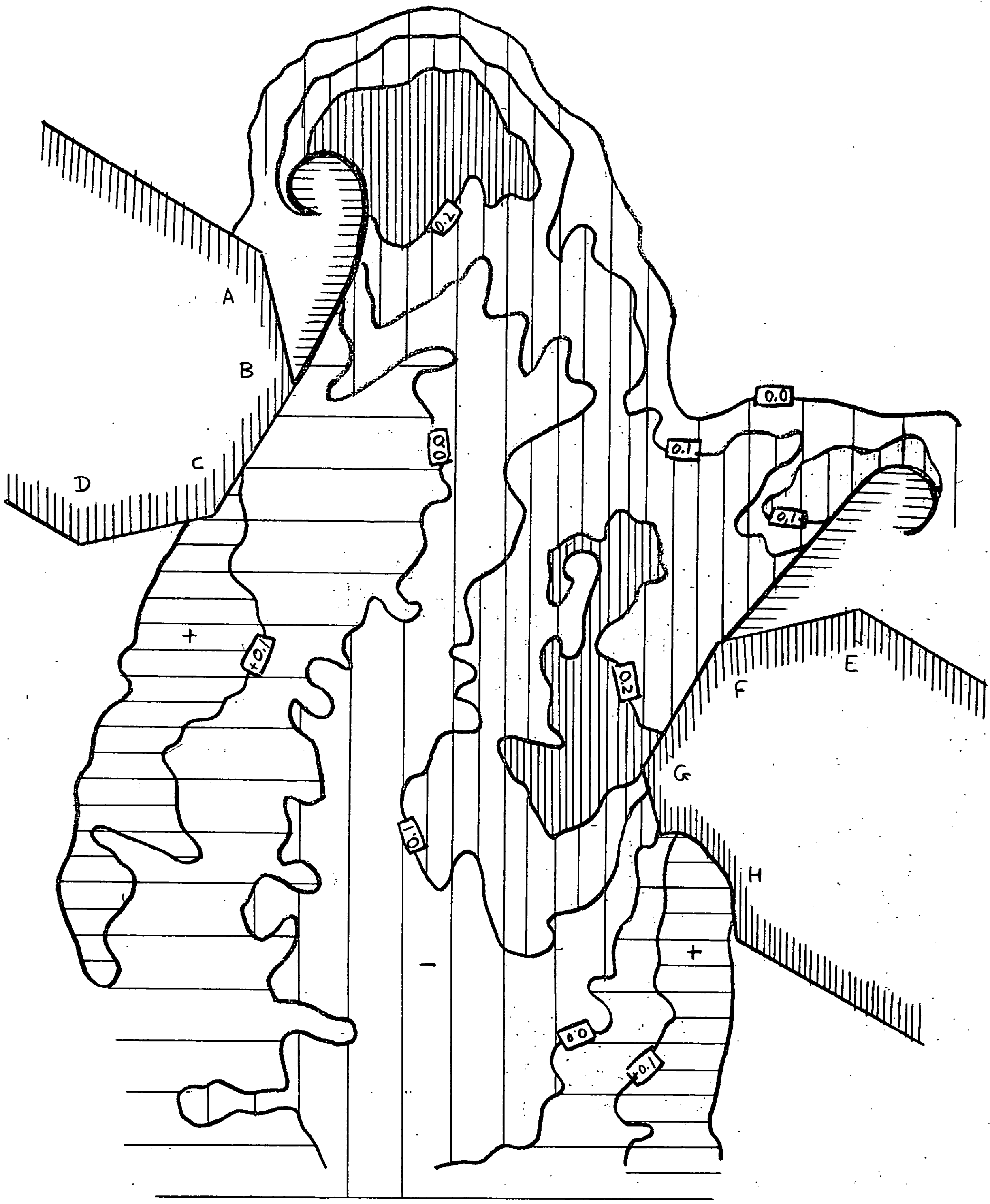
TEST 2: FIG. 6



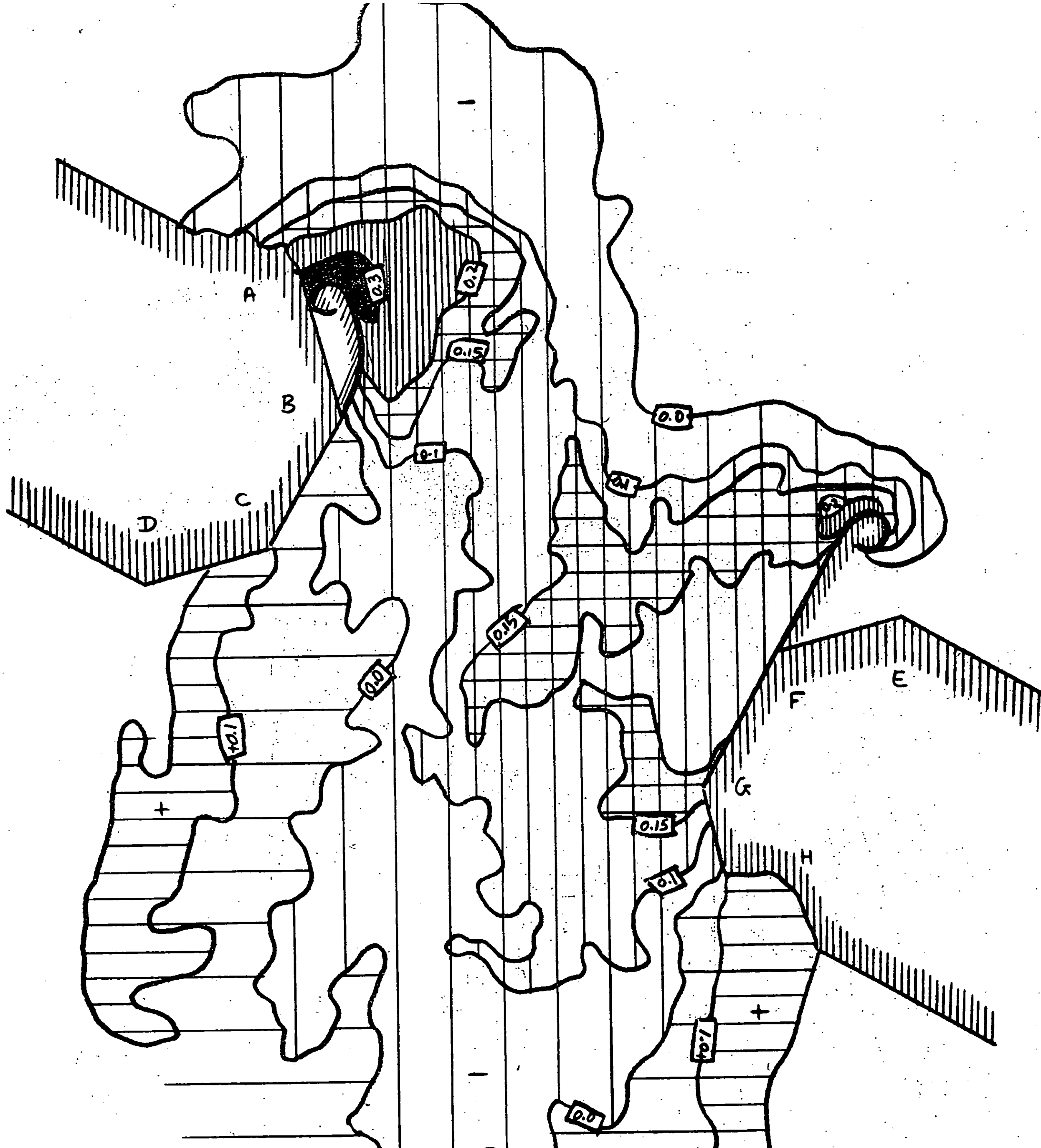
TEST 3: FIG. 7



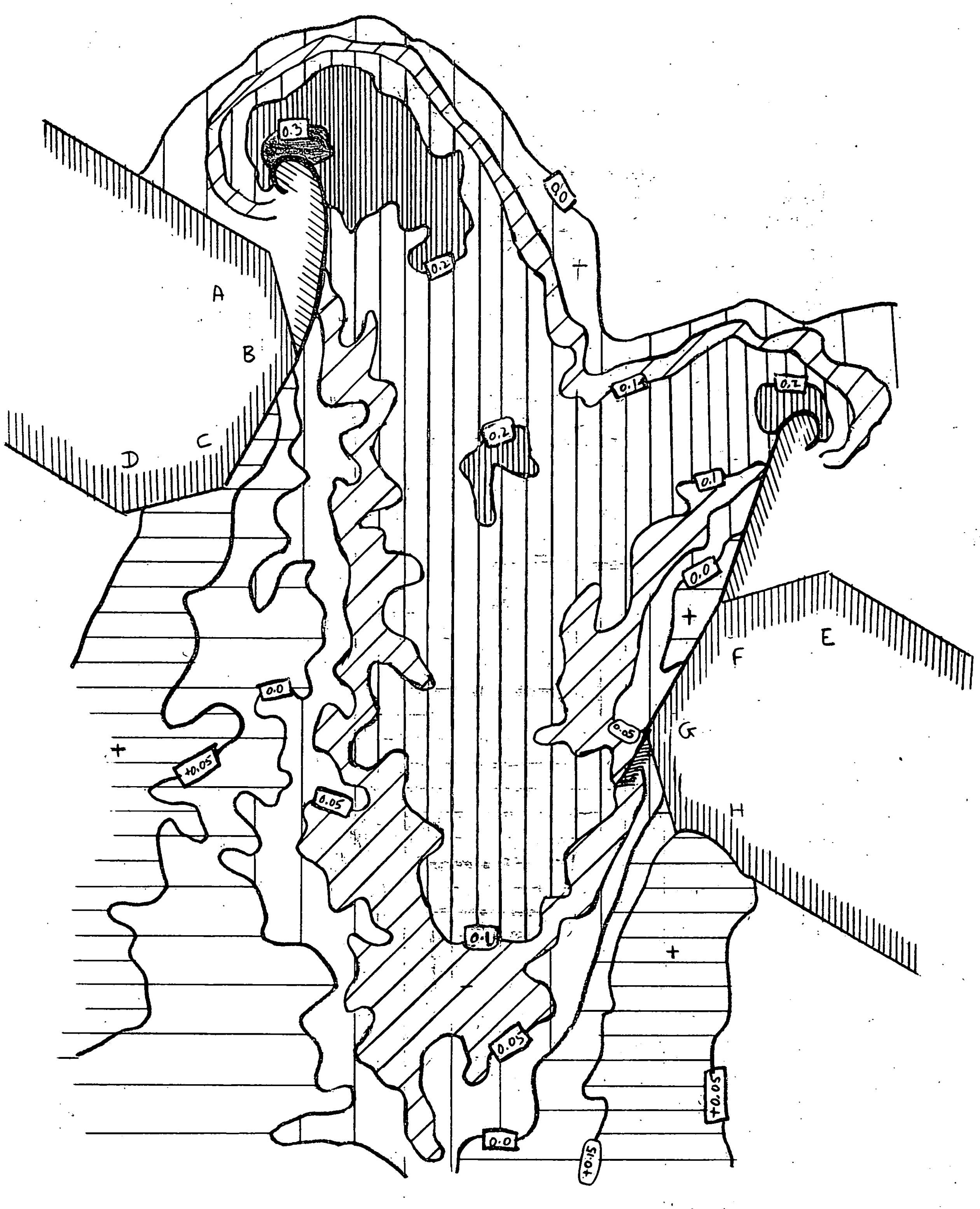
TEST 4: FIG. 8



TEST 5: FIG. 9



TEST 6: FIG. 10



TEST 7: FIG. 11